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Preventing Cascading Failure Through Fuzzy Co-Operative Control Mechanism Using V2G

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ABSTRACT The previously proposed algorithms for preventing cascading failures, which lead to a blackout event, involve specific load shedding schemes, which introduce incurring losses in the power system network. In this paper, a cooperative control based algorithm using a vehicle to grid (V2G) technology based on a fuzzy logic approach is proposed to prevent cascading failures without loss incurrence. The algorithm is implemented on a standard IEEE-30 bus system, and it uses mathematical combinations heuristically to identify the critical nodes through the use of a self-propagation graph to dispatch the optimum power from V2G. For the enhancement of computational speed, a network operator considers only those vulnerable nodes, which are identified by a self-propagating graph. Through this, a network operator can easily detect critical nodes by rooting straight to the vulnerable transmission lines in the IEEE-30 bus network. The probabilistic modeling in this paper is performed in such a way that network operators will mitigate cascading failures events (CFEs) after the occurrence of $(N-1)$ and $(N-1-1)$ contingencies/blackout events without performing load shedding. The detailed experimental analysis provides better visualization of the impact of CFEs on power grids to the power network operators and therefore significantly improves the accuracy of taking necessary actions to compensate these CFEs.

INDEX TERMS Cascading failure events, vehicle to grid technology, IEEE-30 bus network, fuzzy controller.

I. INTRODUCTION

The complexity of the power system network, the interconnection between different components, and the various time-based scale dynamics and interactions in smart grids have made the analysis and modeling of cascading failure events (CFEs) immensely complicated. These CFEs are responsible for triggering an unpredictable form of chain reactions [1]. Some notable examples are the blackouts of Southwest Arizona and Southern California in 2011 [2] and the record-breaking Indian blackout in 2012 [3], which have shown the devastating effects of these chain reactions. However, due to the very high cost required to replace the existing power grid infrastructure with the modern highest standard grid, i.e., the smart grid still has to rely on the existing electric power infrastructure [4]. For smart grids, to prevent these chain reactions, is a challenging research issue, especially after an occurrence of a CFE in a power system network.

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To tackle this problem, the development of various algorithms based on real-time modeling of CFEs is still in its ongoing phase. These algorithms for CFEs can be divided into several categories. For example, the methodology proposed in [5], [6] utilized the phenomena of centrality measures and the modeling based on time dependency and hidden failure for the proper assessment of CFEs in a power system network. For the analysis of CFEs in complex power networks, the authors in [7], [8] proposed a methodology based on a comparative overview of different cascading failures models at the same time. Similarly, for the modelling of cascading failure propagation respectively, the authors in [7], [8] utilize the concept of statistical estimators. Also, the methodology proposed in [9]–[11] suggested the vulnerability analysis, load-dependent, and complex dynamics models of CFEs, respectively. Some of the proposed techniques in literature were based on the severity and the risk related to the occurrence of CFEs in power system networks by considering their adverse effects on power grids [11], [12].

Moreover, to reduce the probability of occurrence of CFEs in the power system network, different types of optimized algorithms have already been proposed in the literature. For example, the modeling based on exposing of hidden protection failures was proposed in [13]. Similarly, the utilization of decentralized and protection algorithms to compensate for CFEs in the power system network was proposed in [14], [15]. Also, the methodology based on a multi-agent system to prevent and predetermine the critical events, which may result in the occurrence of CFEs in a power system network was proposed in [16]–[18]. Similarly, in [19], the authors proposed a stochastic analysis for the prediction of CFEs probability in time. Also, to reduce the probability of CFEs in an interdependent infrastructure, the authors in [20] utilized the concept of an interdependent Markov chain model. Similarly, in [21], [22], the authors portray a detailed study based on a scenario of the scale-free topological network to reduce node failure probabilities to mitigate CFEs in a power system network. Moreover, the development of a novel interdependent system model to capture the events of cascading failures, and thus providing network robustness was proposed in [23].

Recently proposed studies in [24]–[29] utilized the concept of load shedding schemes to mitigate the effects of CFEs in the power system network. In [24], the authors proposed a study based on a multiagent system algorithm to mitigate CFEs using different load shedding schemes. Similarly, in [25], the concept of fair load shedding scheme along with the utilization of decentralized control mechanisms was proposed by authors to prevent CFEs in a power system network. Also, in [26], the authors proposed an optimum decision support systems algorithm based on a power grid load shedding to prevent CFEs in a network. Similarly, for enhancing the power grid resilience against CFEs, the authors in [27] utilized the concept of optimal transmission switching and load shedding at the same time. Also, the merits and demerits of different load shedding schemes to be utilized in a network in terms of its importance as, cost minimization, mitigation of disturbances and provide stability to an overall network was proposed in [28]. Moreover, in [29], the authors portrayed a detailed study based on the modeling of different hidden failure modes and supervised under-voltage load shedding schemes to mitigate the effect of CFEs in a power system network. All of these proposed methodologies in literature were based on two protection schemes. Firstly, performing load shedding to prevent the spreading of CFEs in a power system network. Secondly, taking pre-contingency preventive measures, which are utilized to reduce the probability of occurrence of CFEs.

The problem with the load shedding scheme is that it provides significant losses to all stakeholders. Moreover, the reliability of power grids will also be highly influenced using load shedding schemes. Whereas, in the second case, the power network operators did not visualize accurately the impact of CFEs on power grids, which is very important to take accurate decisions to compensate for any future contingency issue. The proposed work outperforms all of these existing methodologies by preventing the spreading of CFEs without utilizing the load shedding schemes or taking preventive measures. This can be done by using an integration of the vehicle to grid (V2G) cooperative control based technology using a fuzzy logic approach in the IEEE-30 bus power system network. By using this approach, each subsystem in the IEEE-30 bus network knows about the dynamic model of other subsystems to predict future decisions more accurately. This post-contingency preventive measures using V2G in the power system will increase the reliability of power grids. Moreover, it also provides access to network operators to visualize the behavior of the network better in terms of its protection against imminent disturbances.

To prevent the spreading of chain reactions in the form of CFEs in the IEEE-30 bus network without performing load shedding, the network must fulfill the following two conditions. The first one is mitigating an overloading condition in a short period after a contingency [30]. The second one is compensating the effects of transients issues as early as possible, which may lead to cascade failure outages. This problem was highlighted in [31], [32]. To provide an optimal solution to these two critical problems, probabilistic modeling based on an integration of cooperative control V2G technology using a fuzzy logic approach in the power system network is performed in this paper. The fuzzy controller is utilized to detect these overloading conditions and transients delays in the IEEE-30 bus network and gives a feedback signal to V2G for its compensation.

The superiority of the fuzzy controller as compared to conventional controllers for detecting overloading and transients delays is highlighted in [33]–[36]. In the case of using conventional controllers in a network, the main drawback is that its topology depends on the mathematical modeling of the system. Considering a complex network, as in our case, the mathematical modeling of the system is not adequately defined. Inspite of all known parameters, there may be parameter variations arise in a power system network. Due to this reason, it is challenging to design parameters properly for a controller [37]. For this purpose, research has been going on in the form of developing the latest controllers, such as predictive controller [38], H-infinity controller [39], and sliding mode controller [40] to achieve a stable response in a network. All of these control topologies depends on complex metamathematical analysis. To avoid these difficulties, recent research is moving towards designing of an intelligent controller [41]. To achieve the desired results, these intelligent controllers are used to solve many complex metamathematical problems [42]–[44]. A recent study of fuzzy logic controller based on adaptive event-triggered output with packet dropouts and actuator failure for non-linear network systems was proposed in [45]. Similarly, for accurate fault detection and isolation of the discrete-time system, an event-triggered mechanism based on a geometric approach was adapted in [46]. Moreover, the fuzzy logic system based on a multiagent system, which is subject to input quantization and unknown gains in a prescribed performance has been considered in [47]. Considering the above advantages of an intelligent control techniques, a cooperative control mechanism based on the fuzzy logic approach is presented in this paper to mitigate uncertainties arises in the form of CFEs due to unbalanced load and transients stability issues. To the best of the authors' knowledge, this is the first work that stochastically analyzed the impacts of CFEs on power system network after an occurrence of $(N-1)$ and $(N-1-1)$ contingencies events without performing load shedding or taking preventive measures.

Followings are the key contributions of this paper:

1) preventing CFEs in IEEE-30 bus network after occurrence of $(N-1)$ and $(N-1-1)$ contingencies events without load shedding or taking pre-contingency preventive measures,
2) evaluating suitable countermeasures in the form of operating V2G cooperative control technology using a fuzzy logic approach in the power system in an optimum way. This compensates for overloaded conditions and transients issues within a short period and restore the network, and
3) developing a probabilistic model based on V2G cooperative control to prevent chain reactions in the form of CFEs in the IEEE-30 bus network for $(N-1)$ and $(N-1-1)$ contingencies.

The rest of the paper is organized as follows. Section II gives an overview of the methodology in detail. Section III provides a comparative overview of the proposed methodology with existing cascading failure models through simulation results. Finally, section IV concludes the paper along with the discussion of future work.

II. METHODOLOGY

One of the possible solutions to compensate CFEs in power system network is to perform load shedding schemes in an optimum way, as proposed in [24], [25]. Among these load shedding schemes, the one proposed in [25] provides a more valuable solution by proposing an algorithm based on a fair load shedding scheme. In [25], the authors applied this algorithm on a standard IEEE 30 bus power system network to mitigate the spreading of chain reactions in the form of CFEs, which occurred due to power quality disturbances. For IEEE 30 bus network, three transmission lines, i.e., lines (28, 29 and 36) are considered to be the critical ones. A disturbance on these lines will cause a severe contingency issue as was highlighted in [25]. The main idea behind this algorithm is to shed loads on these critical lines in an optimum way using a technique based on a fair load shedding scheme. This paper proposes a methodology, which provides an optimum solution to the problem formulated in [25]. This can be done by compensating CFEs in the IEEE-30 bus network using a V2G cooperative control algorithm based on a fuzzy logic approach without considering the shedding of loads on lines 28, 29 and 36. To verify the proposed methodology, we considered a scenario, in which a three-phase (L-L-L) fault (TPF) has occurred in the IEEE-30 bus network. To avoid the spreading of chain reactions in a form of CFEs in this case, the network must fulfilled the following two conditions in a short span of time, i.e., 1) mitigating of an overloaded conditions on lines 28, 29 and 36 [30], 2) compensating of transients issues due to an arising of TPF on lines 28, 29 and 36 [31], [32]. To avoid tripping of these critical transmission lines in the IEEE-30 bus network, we provide an optimum solution in the form of V2G cooperative control based algorithms using a fuzzy logic approach, as mentioned in Algorithm 1.

Algorithm 1

Input : A set of normal operating states $(n_{a_1}, n_{a_2}, \ldots\ldots, n_{a_n})$, transients delay (d_{e1}) and overloading condition (O_{v1}) on lines 28, 29 and 36 in case of an occurrence of TPF (f_1) in IEEE-30 Bus network

Output: A set of next transition states $(t_{c_j} \rightarrow t_{c_{j+1}})$

while (f_1) **do**
  assign the next transition state to compensate for transients delay (d_{e1}) and overloaded conditions (O_{v1})
  if *IEEE-30 bus network* → *Lines 28, 29 and 36* → *vulnerable to tripped* **then**
    Next transition, $t_{c_{j+1}} \rightarrow$ V2G cooperative control
  else
    next transition, $t_{r_{j+1}} \rightarrow (n_{a_1} \rightarrow n_{a_n})$
  end
  Send $t_{c_{j+1}}$ transition state as an input to Algorithm 1
end

For this purpose, a closed-loop demand response probabilistic model is designed, as shown in Fig. 1. Through this, the network operators regularly monitor an overloaded and transients responses on lines 28, 29, and 36 of the IEEE-30 bus network using a cooperative control V2G technology based on a fuzzy logic approach. This reduces the spreading of chain reactions in the form of CFEs in IEEE-30 bus network, even after an occurrence of a contingency event on lines 28, 29 and 36. The terminologies used in Fig. 1 are discussed in section-D of mathematical modeling.

III. MATHEMATICAL MODELING

For the proper assessment of the stability region in a power system network, [48]–[51] proposed a model based on algebraically derived expressions. To ensure power system network to its stable region even in case of transients and overloading conditions due to TPF, the network Thevenin impedance and the generator injection impedance must fulfill,

$$Z_{inj} \geq \frac{-Z_{th} sin\varphi_{inj}}{sin\varphi_{th}}. \tag{1}$$

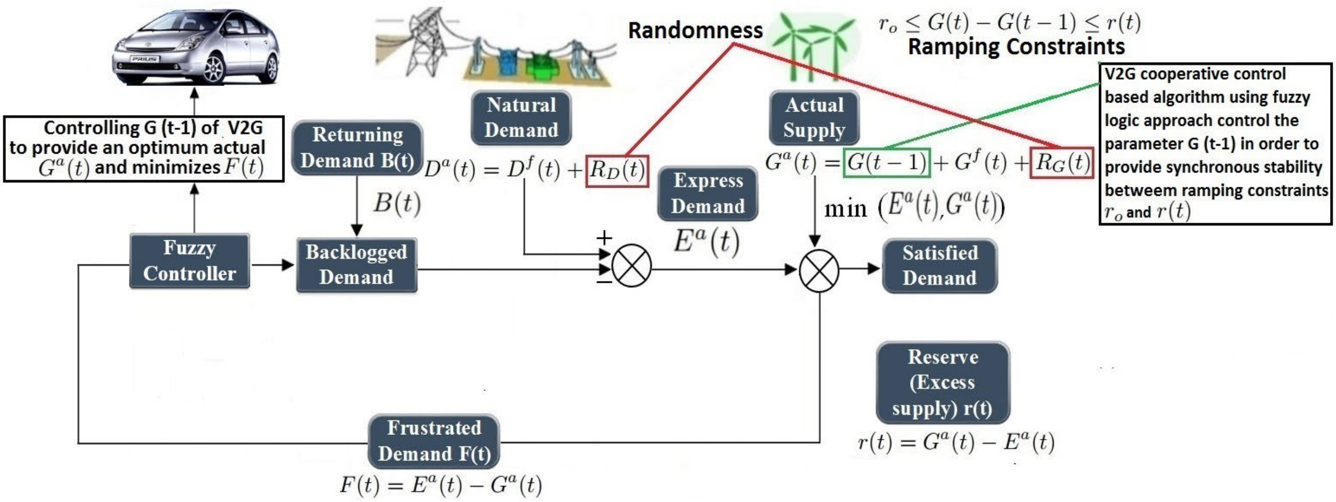

FIGURE 1. Demand response probabilistic schematic model.

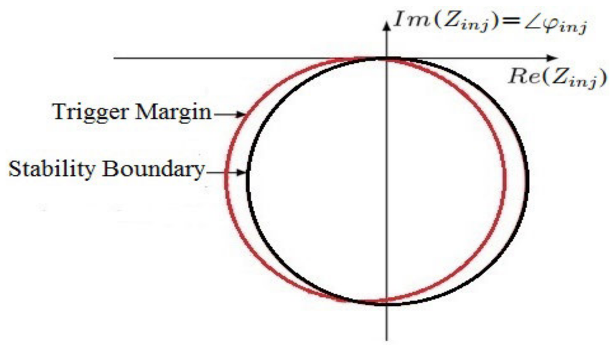

FIGURE 2. Generator injection impedance plane for stability boundary.

Here, the generator injection impedance is $Z_{inj} = Z_{inj}\angle\varphi_{inj}$ with $Z_{inj} \geq 0$. Whereas, the power network thevinin impedance is $Z_{th} = Z_{th}\angle\varphi_{th}$ with $Z_{th} \geq 0$.

If the network does not meet the desired condition in (1) due to overloading and transients issues, arise on lines 28, 29, and 36 of the IEEE-30 bus network. Then an enhancement in the generators' rotor angle occurred connected on these lines, which will subsequently minimize the electrical output of the machine rather than increasing it. Now, if the generator prime mover mechanical torque is not reduced, then causes a mismatch between generator electrical and mechanical torque. Due to which, the generator starts to accelerate, leading to the loss of synchronization.

Equation (1) appears in the form of a circle in the generator injection impedance plane, as shown in Fig. 2. The stability boundary is indicated by the circle with black color, as shown in Fig. 2. Outside this circle, the network moves towards an unstable state; therefore, some remedial action must be executed before the network completely moves to an unstable state. Hence, a trigger margin is introduced in Fig. 2, which provides information about the percentage of maximum injection power from the generator and thus represents the threshold stability margin below which the countermeasure is executed. This trigger margin is indicated using a fuzzy logic controller. Whereas, V2G acts as a countermeasure, which is applied before the network moves completely to an unstable state to retain the stability boundary in Fig. 2.

A. IDENTIFICATION OF CRITICAL NODES FOR COUNTER MEASURE APPLICATIONS

1) SENSITIVITY ANALYSIS

Considering (1), the network operator can easily identify those power grid nodes that have a critical impact on the stability of the generator, i.e., lines 28, 29 and 36 of the IEEE-30 bus network. Considering this scenario, the sensitivity matrix S_k is defines, where the matrix elements can be determined according to

$$S_{inj} = \frac{\partial \frac{Z_{th}}{\sin\varphi_{th}}}{\partial Y_{m,m}} \frac{\partial K_{th_k}}{\partial Y_{m,m}}. \tag{2}$$

where, the index K and m represent the generator and load nodes of lines 28, 29 and 36 of the IEEE-30 bus network. This algorithm based on the sensitivity analysis technique for the identification of those critical nodes, which have a severe impact on the stability of the generators was proposed in [52].

2) SELF PROPAGATION GRAPH

As we already discussed, to reduce the probability of CFEs after an occurrence of contingency event, the network must provide an overloading and transients compensation within a short period. For this purpose of making the processing speed faster, a technique based on a self-propagation graph was proposed in [53]. This type of graph is utilized for the identification of those critical nodes as soon as possible, which has a critical impact on lines 28, 29 and 36 of the IEEE-30 bus network. These nodes can be identified by using a controller based on a fuzzy logic approach. This self-propagation graph makes the processing speed faster by excluding those nodes,

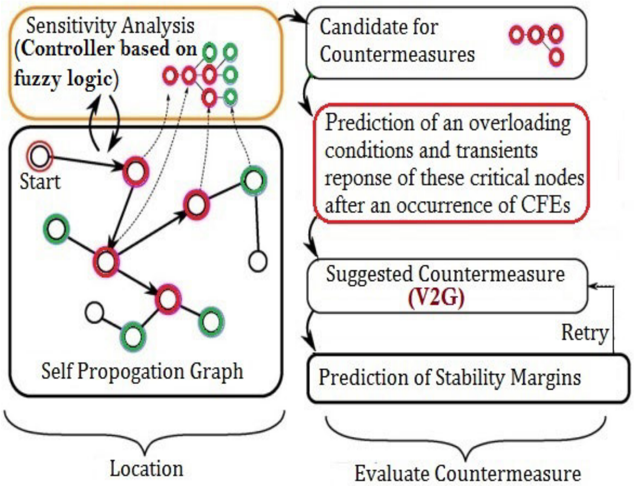

FIGURE 3. Self propagation graph for identifying the critical nodes.

which are having a minimum influence on a power system network. After identifying the critical nodes, they are passed through countermeasure applications, i.e., in our case V2G, which provides an optimum compensation of those critical nodes, which are identified by a self-propagation graph as shown in Fig. 3.

B. TRANSIENTS DELAY MODEL

For the prediction of transients responses, a delay-based model proposed in [54], [55] is described below,

$$A_{t_d} = \frac{1}{\lambda_{td}}. \tag{3}$$

C. OVERLOADING FAILURE MODEL

One of the most influential factors, which leads the chain reaction in the form of CFEs is the tripping of a generation branch [56], [57]. Therefore, a generator tripping each time in the IEEE-30 bus network is represented with a CFEs. In this paper, each time a CFE occurred in a power system network, it suddenly leads to an overloading condition on a generation branch l. Due to this, a sudden enhancement in power flows F_l occurred, especially from its thermal rating power flow, which is represented with C_l. Using the model of generation branch overloading l, the critical impact of an overloading condition on an IEEE-30 bus network, as formulated in [56] and [57] can be represented as,

$$O(l, t) = \int_{t_o}^{t} [F_l(t) - C_l]dt \quad F_l(t) > C_l, \tag{4}$$

where the power flow in the generation branch at time t is represented with $F_l(t)$. Overloading of power system network at a time t is represented with $O(l, t)$ and it is integrated from t_0 to t, considering steady-state assumption in IEEE-30 bus network. In other words, it represents the time intervals, when overloading occurred in the IEEE-30 bus network, while it remains in a steady-state position. Now, considering the issue of load demand curtailments on lines 28, 29 and 36 of IEEE-30 bus network, a random deviations occurred in power flow F_l, which correspondingly changes the overloaded duration time, i.e., t_0 to t. Due to which, the power system network will not remain in their steady-state position. Now, with the changes of state, the accumulative function $O(l, t)$ moves suddenly to a dangerous threshold limit, i.e., $O_{limit}(l)$ at a time $T_f(l)$. To minimize this $O_{limit}(l)$, an overloading generation branch l, i.e., lines 28, 29 and 36 of the IEEE-30 bus network are accommodated using a V2G cooperative control based algorithm based on fuzzy logic approach. In this case, through using V2G technology, the network operators can control the charge of the batteries and use the available power to regulate critical transmission lines 28, 29, and 36 of the IEEE-30 bus network. This will reduce the probability of an occurrence of CFEs, even after an arising of a contingency event. The ramping time period model T_{ramp} for this V2G technology can be defined as,

$$T_{ramp} = \min_{I \epsilon L}[T_f(l)], \tag{5}$$

where, $T_f(l)$ represents the time period at which a critical overloading $O_{limit}(l)$ occurred in IEEE-30 bus network as expressed in (6). To minimize $O_{limit}(l)$, fuzzy controller is utilized in IEEE-30 bus network, which senses these critical overloading conditions $O_{limit}(l)$ at time $T_f(l)$ of lines 28, 29 and 36 and correspondingly operates V2G at ramping time period of T_{ramp} in (5) to mitigate these critical situations,

$$O(limit, t) = \int_{t_o}^{t_o+T_{ramp}} [F_l(t) - C_l]dt \quad F_l(t) > C_l. \tag{6}$$

Considering (5) and (6), an optimum balanced response is achieved between generation and demand by using a V2G cooperative control based technology using a fuzzy logic approach.

D. V2G PROBABILISTIC MODELING FOR COUNTERMEASURE

Considering contingencies in the form of CFEs, the V2G probabilistic modeling aims at finding out the optimal generation from V2G. In this modeling, we can minimize the frustrated demand $F(t)$, as shown in Fig. 1 by equalizing the forecast demand $D^f(t)$ according to forecast supply $G^f(t)$. A closed-loop control system is modeled for this purpose is shown in Fig. 1.

Through this modeling technique, an overloading condition on lines 28, 29, and 36 are compensated. For this purpose, $G^f(t)$ and $D^f(t)$ are incorporated in a closed-loop system. To mitigate the effects of an overloading condition in IEEE-30 bus network, a synchronous stability between $G^f(t)$ and $D^f(t)$ is achieved using a V2G technology based on fuzzy logic approach, i.e.,

$$G^f(t) = D^f(t) + r_o, \tag{7}$$

where, the nominal reserve is represented with r_o, which represents an optimum supply form V2G. In this case, a synchronous stability between $G^f(t)$ and $D^f(t)$ is achieved by updating the $B(t)$ returning demand continuously. This can be done by adjusting r_o using V2G technology.

To verify the above scenario through probabilistic modeling, we analyze the effect of CFEs. For this purpose, we consider λ_i to be a TPF delay time slot, i.e., average delay (A_d), which can be expressed as,

$$A_d = \lambda_i. \tag{8}$$

The above average delay corresponds to one time slot. Whereas, the generalized version of (8) in a form of a closed loop probabilistic model as shown in Fig. 1 can be represented with,

$$A_d = \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right), \tag{9}$$

where, λ_{i_1} represents the TPF delay for each closed loop iteration. Whereas, n_1 represents the effect of TPF on critical lines 28, 29 and 36 of IEEE-30 bus network, ($n_1 = 3$).

Similarly, to address the real time demand response, we considered a synchronous stability between $D^f(t)$ and actual demand $D^a(t)$, i.e.,

$$D^a(t) = D^f(t) + R_D(t). \tag{10}$$

where $R_D(t)$ represents the randomness between $D^a(t)$ and $D^f(t)$. After A_d model incorporation in (10), it can be expressed as,

$$D^a(t) = \left\{\left[D^f(t) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] + R_D(t)\right\}. \tag{11}$$

Similarly, $D^a(t)$ must be changed according to generation injection impedance, network Thevinin impedance and sensitivity matrix S_K as modelled in (1) and (2) and also with the transients delay and overloading based probabilistic modelling of (3) and (6). Therefore, by incorporating these models in (11), it can be re-expressed as,

$$D^a(t) = \left\{\left[D^f(t) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[Z_{inj} \times S_{inj}\right] \times \left[\frac{1}{\lambda_{t_d}}\right] \times \left[O(limit, t)\right] + R_D(t)\right\}. \tag{12}$$

Now, to continuously monitor the overloading conditions between demand and generation response in order to avoid tripping of critical lines 28, 29 and 36 of IEEE-30 bus network, (12) can be represented in terms of a closed loop generalized form as,

$$D^a(t) = \sum_{i=1}^{n}\left\{\left[D_i^f(t) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[Z_{inj_i} \times S_{inj_i}\right] \times \left[\frac{1}{\lambda_{t_{d_i}}}\right] \times \left[O_i(limit, t)\right] + R_{D_i}(t)\right\}, \tag{13}$$

where, $R_D(t)$ can be found out using an auto-correlation probabilistic modelling represented as,

$$R_D(t) = E[D^a(t)D^f(t)], \tag{14}$$

when, $D^a(t)$ approaches to $D^f(t)$, $R_D(t)$ approaches to zero. Through this, an overloading conditions on lines 28, 29 and 36 is easily resolved. This can be done by operating V2G using controller based on fuzzy logic approach, i.e.,

$$G^f(t) = D^f(t). \tag{15}$$

Similarly, to address a real time generation response, there must be a synchronous stability between an actual supply $G^a(t)$ and previous supply $G(t-1)$.

$$G^a(t) = G(t-1) + G^f(t) + R_G(t), \tag{16}$$

where, the random deviations between $G^a(t)$ and $G^f(t)$ is represented with $R_G(t)$.

Where, the control parameter is represented with $G(t-1)$, which moves back the power system network to a one-time slot before in a real-time scenario. Through this, the network operators easily accomplished the target of achieving the desired load and minimizing the overloading conditions on lines 28, 29, and 36. $G(t-1)$ is controlled through V2G cooperative control based technology using a fuzzy logic approach to provide an optimum $G^a(t)$ as shown in Fig. 1.

Now, by incorporating the previous proposed model in (1), (2), (3) and (6) along with an average delay model in (9), the generalized form of (16) an be represented as,

$$G^a(t) = \sum_{i=1}^{n}\left\{\left[G_i(t-1) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] + \left[G_i^f(t) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[Z_{inj_i} \times S_{inj_i}\right] \times \left[\frac{1}{\lambda_{t_{d_i}}}\right] \times \left[O_i(limit, t)\right] + R_{G_i}(t)\right\}, \tag{17}$$

whereas, the optimum value of $R_G(t)$ is determined through an auto-correlation probabilistic model as expressed in (18),

$$R_G(t) = E[G^a(t)G^f(t)]. \tag{18}$$

Similarly, when $G^a(t)$ approaches to $G^f(t)$, $R_G(t)$ approaches to zero. Through this, we can minimize the random deviations between $G^f(t)$ and $D^f(t)$.

To make $R_G(t)$ approaches to zero forcefully, a tuning of $G(t-1)$ on lines 28, 29 and 36 of the IEEE-30 bus network can be performed using a fuzzy logic controller in an optimum way based on the self-propagation graph as shown in Fig. 3. After this, a signal is generated from the fuzzy logic controller towards V2G, which provides an extra power to mitigate overloading conditions on these lines. Through this, a synchronous stability between $G^f(t)$ and $D^f(t)$ is achieved.

The shortage of an active power after an occurrence of contingency event in IEEE-30 bus network can be represented in terms of frustrated demand $F(t)$ as,

$$F(t) = E^a(t) - G^a(t), \tag{19}$$

where the expressed demand is represented with $E^a(t)$. To provide a balanced load between demand and generation response, $E^a(t)$ must be satisfied in the desired time interval.

The power system should be in $F(t)$ state, when

$$E^a(t) > G^a(t). \tag{20}$$

After incorporating the model in (1), (2), (3) and (6) along with an average delay model in (9), (19) can be re-expressed as,

$$F(t) = \sum_{i=1}^{n}\left\{\left[\left(E_i^a(t) - G_i^a(t)\right) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[Z_{inj_i} \times S_{inj_i}\right] \times \left[\frac{1}{\lambda_{td_i}}\right] \times \left[O_i(limit, t)\right]\right\}. \tag{21}$$

If there is a random deviations between demand and response, then the system represents these deviations in a form of $F(t)$ as shown in Fig. 1. This $F(t)$ continue the feedback path and received to the power system network in terms of returning/backlogged demand $B(t)$ along with an association of closed loop delay λ_{c_1}. Therefore, $B(t)$ expression will be represented in a form of $F(t)$ as shown in (19) along with the multiplication of λ_{c_1},

$$B(t) = \sum_{c_1=1}^{n_1}\left(\frac{1}{\lambda_{c_1}}\right) \times \left(E^a(t) - G^a(t)\right). \tag{22}$$

Now, (22) can be rewritten as,

$$B(t) = \sum_{c_1=1}^{n_1}\left(\frac{1}{\lambda_{c_1}}\right) \times \sum_{i=1}^{n}\left\{\left[\left(\frac{E_i^a(t) - G_i^a(t)}{n}\right) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[Z_{inj_i} \times S_{inj_i}\right] \times \left[\frac{1}{\lambda_{td_i}}\right] \times \left[O_i(limit, t)\right]\right\}. \tag{23}$$

The expression for the reserve $r(t)$ should be,

$$r(t) = G^a(t) - E^a(t). \tag{24}$$

There must be reserve required in IEEE-30 bus network, when,

$$G^a(t) > E^a(t). \tag{25}$$

Equation (25) can be rewritten as,

$$r(t) = \sum_{i=1}^{n}\left\{\left[\left(G_i^a(t) - E_i^a(t)\right) \times \frac{1}{n_1}\sum_{i_1=1}^{n_1}\left(\lambda_{i_1}\right)\right] \times \left[Z_{inj_i} \times S_{inj_i}\right] \times \left[\frac{1}{\lambda_{td_i}}\right] \times \left[O_i(limit, t)\right]\right\}. \tag{26}$$

The threshold policy for reserve $r(t)$ requirements is, if

$$r(t) < r_0. \tag{27}$$

Then we must increase $G^a(t)$ by controlling $G(t-1)$ through V2G cooperative control based technology using a fuzzy logic approach as shown in Fig. 1. This will minimizes the $F(t)$ and make $r(t)$ approaches to r_0 as close as possible. This can be done through ramping up constraints using V2G, otherwise if,

$$r(t) > r_0, \tag{28}$$

then, we must decrease $G^a(t)$ using an optimum generation from V2G to make $r(t)$ approaches to r_0 as close as possible. This can be done through ramping down constraints using V2G. Whereas, ramping constraints can be expressed as,

$$r(t) \leq G(t) - G(t-1) \leq r_o. \tag{29}$$

From (16), $G(t) - G(t-1)$ can be formulated as,

$$r(t) \leq G^f(t) + R_G(t) \leq r_o. \tag{30}$$

The critical problem here is to handle $B(t)$ in every case. This can be done through minimizing $R_G(t)$ using V2G, which provides optimal control in the form of synchronization between $r(t)$ and r_0, considering the ramping up and down constraints form (27) and (28).

Therefore, after an $R_G(t)$ minimization, (30) can be represented as,

$$r(t) \leq G^f(t) \leq r_o, \tag{31}$$

From (7), the synchronous stability between $G^f(t)$ and $D^f(t)$ can be achieved, i.e.,

$$r(t) \leq D^f(t) \leq r_o. \tag{32}$$

Through (32), an optimum load flow balancing is achieved on lines 28, 29 and 36 of the IEEE-30 bus network using a V2G cooperative control based fuzzy logic approach, which mitigates the effect of CFEs.

Here, V2G will not only contribute to compensate the fluctuating critical nodes, i.e., lines 28, 29 and 36 in IEEE-30 bus network, but it should also be considered as a resourceful technology to mitigate the effects of transients issues on these transmission lines. To verify this scenario, we considered $D_{t_1}^f$ as a forecast demand during arising of transients' issues and $V_{t_1}^f$ as the forecast supply through V2G for it's mitigation. Our control problem is to determine an optimal value for the dispatched power schedule $P_t^f(t+f)$, through which the power system network operators can provide an enhancement in transients response and power dispatchability. This can be done by using fuzzy logic controller, which sets the parameters of $P_t^f(t+f)$ equals to $(D_t^f(t+f) - U_t^f(t+f) + r_o)$, where an r_0 is either positive or negative, considering the value of ramping up and down constraints of (27) and (28). Therefore, $P_t^f(t+f)$ final expression can be represented as,

$$\sum_{i=1}^{n}\left\{\left[P_{t_i}^{f_i}(t_i+f_i)\right] = \sum_{i=1}^{n}\left[\left(D_{t_i}^{f_i}(t_i+f_i)\right) - \left(V_{t_i}^{f_i}(t_i+f_i)\right)\right] \times \left[Z_{inj_i} \times S_{inj_i}\right] \times \left[\frac{1}{\lambda_{td_i}}\right] \times \left[O_i(limit, t)\right]\right\}. \tag{33}$$

TABLE 1. Load Shedding results for selected line contingencies with the IEEE 30 bus system.

Shed loads at each bus (MW) **(Part-A)** [25]							
Line ID	B7	B8	B10	B17	B19	B20	B21
28	0.186	0.635	0.125	0.298	0.114	0.057	0
29	0.852	1.440	0.772	0.999	0.758	0.47	7.515
36	1.447	7.247	0	0	0	0	0
28, 29	1.464	2.136	1.323	1.723	0.506	0.79	7.357
28, 36	2.387	8.637	0.091	0.230	0.081	0.099	0
29, 36	3.029	9.418	0.680	0.907	0.667	0.378	7.423
B_T	**9.365** $r_1(t)$	**29.513** $(N-1)$, **29.713** $(N-1-1)$ $r_2(t)$	**2.991** $r_3(t)$	**4.157** $r_4(t)$	**2.126** $r_5(t)$	**1.794** $r_6(t)$	**22.295** $r_7(t)$
B_T	**-9.365** R_{G_1}	**-29.513** $(N-1)$, **-29.713** $(N-1-1)$ R_{G_2}	**-2.991** R_{G_3}	**-4.157** R_{G_4}	**-2.126** R_{G_5}	**-1.794** R_{G_6}	**-22.295** R_{G_7}
V2G cooperative control based algorithm without load shedding (MW) **(Part-B) (N-1 contingency)**							
Line ID	B7	B8	B10	B17	B19	B20	B21
28	0.198	0.637	0.138	0.320	0.131	0.065	0
29	0.864	1.443	0.784	1.023	0.773	0.48	7.530
36	1.459	7.250	0	0	0	0	0
28, 29	1.476	2.139	1.335	1.744	0.521	0.80	7.372
28, 36	2.399	8.640	0.099	0.251	0.096	0.106	0
29, 36	3.041	9.421	0.696	0.928	0.676	0.385	7.438
B_T	**9.437** r_{0_1}	**29.530** $(N-1)$ r_{0_2}	**3.052** r_{0_3}	**4.266** r_{0_4}	**2.197** r_{0_5}	**1.836** r_{0_6}	**22.340** r_{0_7}
B_T	**0.072** R_{G_1}	**0.017** $(N-1)$ R_{G_2}	**0.061** R_{G_3}	**0.109** R_{G_4}	**0.071** R_{G_5}	**0.042** R_{G_6}	**0.045** R_{G_7}
V2G cooperative control based algorithm without load shedding (MW) **(Part-C) (N-1-1 contingency)**							
Line ID	B7	B8	B10	B17	B19	B20	B21
28	0.192	0.677	0.130	0.310	0.125	0.061	0
29	0.858	1.472	0.778	1.010	0.766	0.476	7.525
36	1.452	7.280	0	0	0	0	0
28, 29	1.469	2.168	1.328	1.734	0.515	0.796	7.367
28, 36	2.394	8.671	0.092	0.240	0.090	0.102	0
29, 36	3.035	9.461	0.688	0.918	0.670	0.383	7.433
B_T	**9.400** r_{0_1}	**29.729** $(N-1-1)$ r_{0_2}	**3.016** r_{0_3}	**4.212** r_{0_4}	**2.166** r_{0_5}	**1.818** r_{0_6}	**22.325** r_{0_7}
B_T	**0.035** R_{G_1}	**0.016** $(N-1-1)$ R_{G_2}	**0.025** R_{G_3}	**0.055** R_{G_4}	**0.04** R_{G_5}	**0.024** R_{G_6}	**0.03** R_{G_7}

where the V2G optimum supply is represented with $V_t^f(t+f)$. Through the above probabilistic modeling, the power network operators can quickly investigate the problem of reliability indices in the form of delays in power systems, and therefore mitigates the effect of CFEs.

IV. SIMULATION RESULTS

Matlab is used as a simulation toolbox for the validation of our proposed analysis. To verify the effectiveness of our proposed algorithm, we simulate it both for $(N-1)$ and $(N-1-1)$ contingencies. Similarly, to mitigate transients' effects after occurrence of CFEs, we outperform the proposed algorithm in [58] based on a distributed non-linear robust controller with the one suggested in this work, i.e., V2G cooperative control based algorithm.

A. COMPENSATION OF AN OVERLOADED CONDITIONS

To mitigate overloading after an arising of CFEs, [25] proposed an algorithm based on a fair load shedding scheme. In [25], the authors applied this algorithm on a standard IEEE 30 bus network. In IEEE 30 bus network, three transmission lines, i.e., (lines 28, 29 and 36) are considered to be the critical ones. A disturbance on these lines will cause a severe contingency issue in the form of CFEs in the IEEE-30 bus network, and this idea was highlighted in [25]. The proposed algorithm of fair load shedding scheme in [25] was also applied to these transmission lines in case of an occurrence of disturbances, i.e., $(N-1)$ and $(N-1-1)$ contingencies. The main idea behind this algorithm is to shed loads on these critical lines in an optimum way using a technique based on a fair load shedding scheme. Critical lines 28, 29, and 36 in the IEEE-30 bus network includes Buses B7, B8, B10, B17, B19, B20, and B21 as highlighted in Fig. 4. To mitigate overloading in all of these buses, authors in [25] shed loads on these critical buses as shown in part-A of Table 1.

In our case, instead of load shedding, we provide an optimal solution to this problem using V2G cooperative control technology. For this purpose, we first identified critical buses in IEEE 30 bus network, as shown in Fig. 4. This can be done using a self-propagation graph, as shown in Fig. 3. After identifying these critical buses, the overloading failure model, as expressed in (6), is then utilized to determine the overloading conditions in the IEEE-30 bus network. To determine the exact range of overloading limits on critical buses, as highlighted in Fig. 4 to take accurate decisions, the concept of a fuzzy controller is utilized. For this purpose, we have given certain inputs to the fuzzy controller. The first input to the fuzzy controller is the overloading factor, which is the ratio of $O(l,t)$ to $O(limit,t)$ as expressed in (4) and (6), i.e.,

$$O_{F_l} = \frac{O(l,t)}{O(limit,t)} \tag{34}$$

O_{F_l} is only considered in IEEE-30 bus network, when $O_{F_l} \geq 1.794$ ($r_6(t)$), i.e., the minimum required active power on critical Bus B20, as shown in part-A of Table 1, from where the overloading starts, otherwise $O_{F_l} = 0$. The overloading membership functions of fuzzy controller is shown in Fig. 5 for $(N-1)$ contingency and Fig. 6 for $(N-1-1)$ contingency, both of which is in normal mode, when $O_{F_l} \leq 1.793$

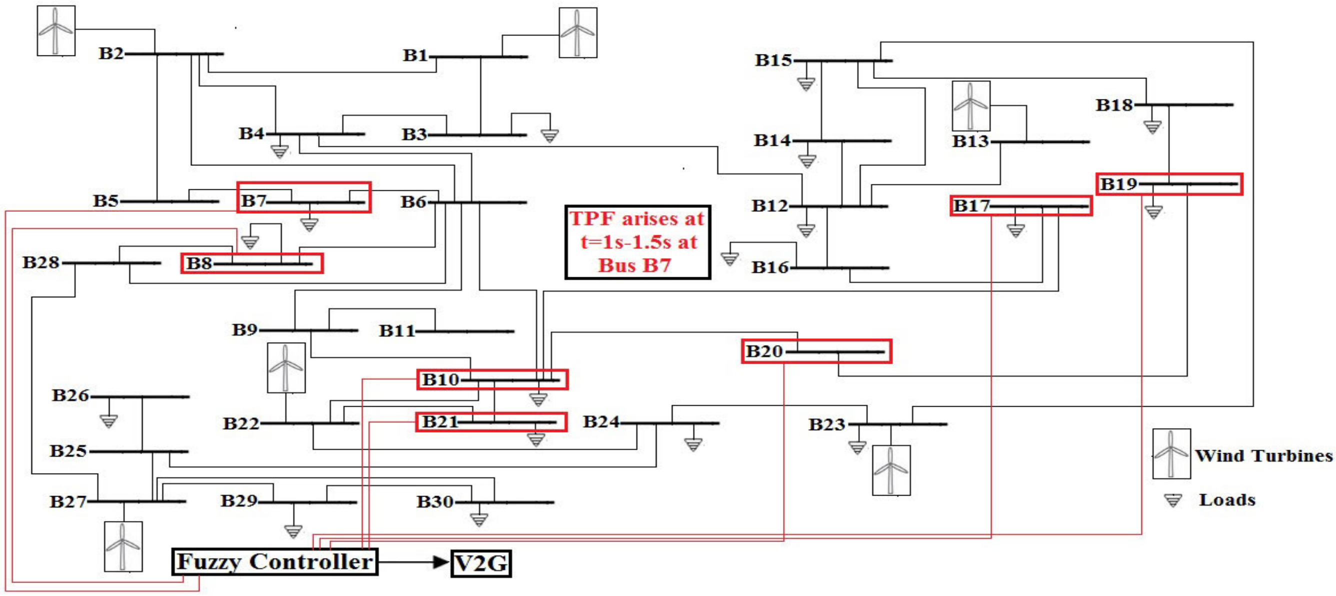

FIGURE 4. IEEE-30 bus network.

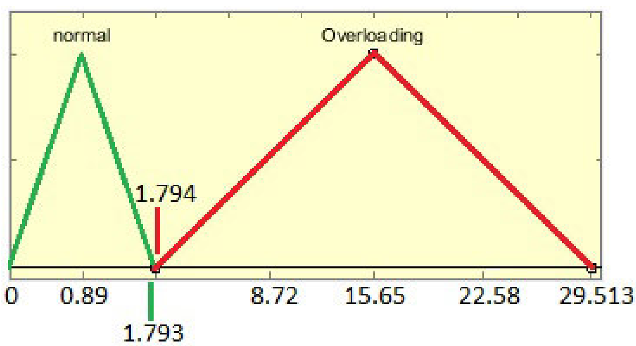

FIGURE 5. Membership function for normal and overloading mode (N-1 Contingency).

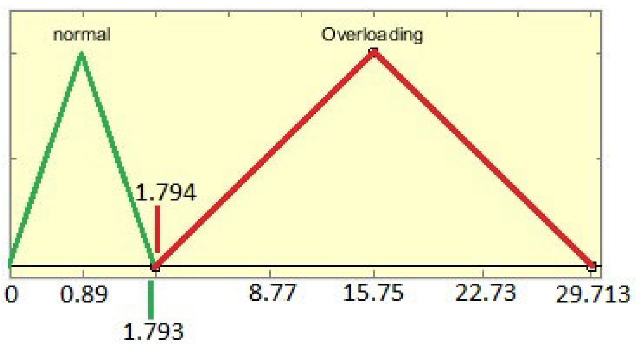

FIGURE 6. Membership function for normal and overloading mode (N-1-1 Contingency).

and in overloading mode, when $O_{F_l} \geq 1.794$. The second input to fuzzy controller is the generator sensitivity factor (GSF), which gives us information about the change occurred in $O(l, t)$ due to random fluctuations in a generator. Initially, $O(l, t)$ is computed, when the system is in a steady state, i.e., $O^0(l, t)$. Then, when a generator is disturbed due to an occurrence of $(N-1)$ and $(N-1-1)$ contingencies in IEEE-30 bus network, a random fluctuation occurred in generation as represented with ΔP_{G_i}. In this case, again a new value of $O(l, t)$ is computed, i.e., $O^{new}(l, t)$. Finally, the ratio of a change in $O(l, t)$ to a change in generation ΔP_{G_i} will give us information about GSF, i.e.,

$$GSF = \left(\frac{O^{new}(l, t) - O^0(l, t)}{\Delta P_{G_i}} \right). \tag{35}$$

This process is repeated for all generators connected in an IEEE-30 bus network. This will give us a GSF matrix $(t_l \times g)$, where, t_l is the number of transmission lines and g is the number of generators connected in IEEE-30 bus network. The fuzzy controller is only operated, when the GSF is exceeding the dangerous overloading threshold limit $O(limit, t)$, i.e.,

$$GSF = \left(\frac{O^{new}(l, t) - O^0(l, t)}{\Delta P_{G_i}} \right) > O(limit, t) \tag{36}$$

After identifying the accurate range of overloading limits, a feedback signal is generated from fuzzy controller towards V2G, which is integrated in IEEE-30 bus network. V2G provides an optimum supply to these critical buses and resolves the problem of overloading without shedding of loads on these buses, in case of an occurrence of $(N-1)$ and $(N-1-1)$ contingencies, as shown in part-B and part-C of Table 1. The step by step response of how each algorithm works, i.e., load shedding algorithm as suggested in [25] and our proposed algorithms both for $(N-1)$ and $(N-1-1)$ contingencies are discussed in the next section.

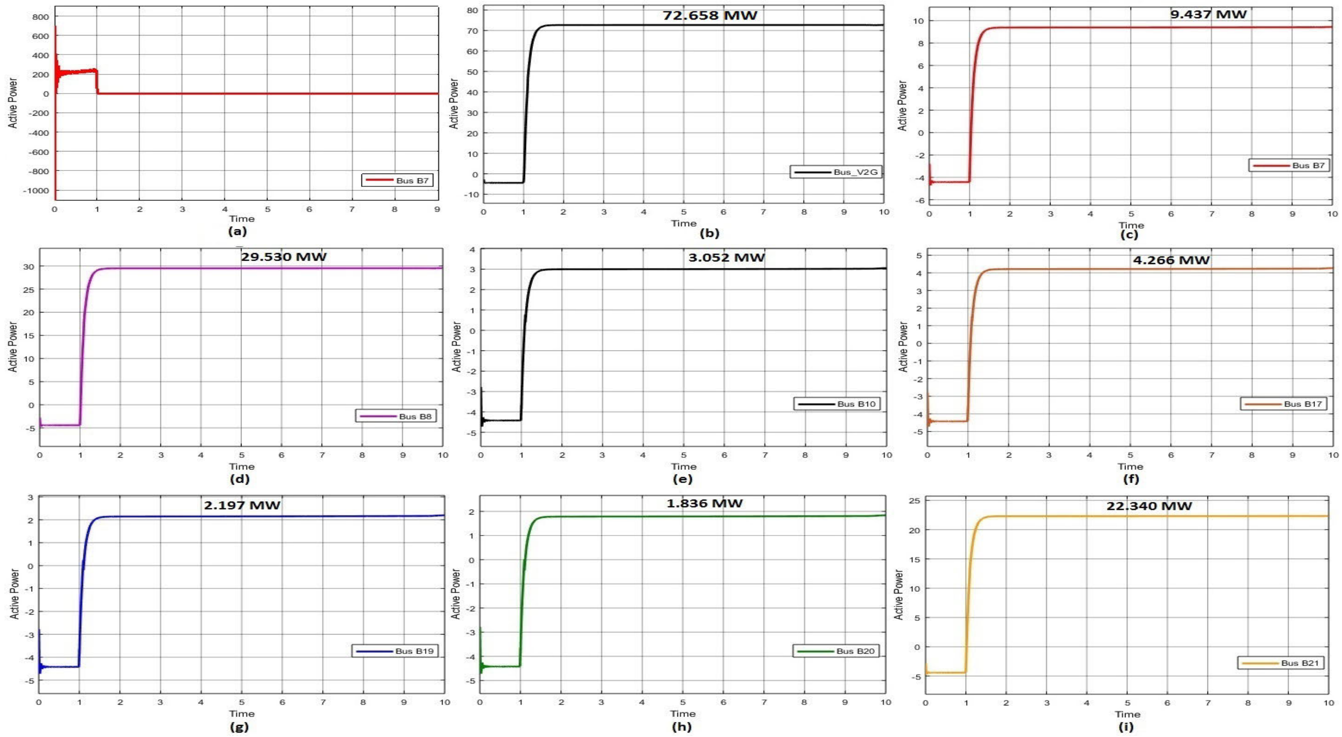

FIGURE 7. a) Tripping of Bus B7 at t = 1s (N-1 Contingency) b) total active power supply from V2G c) V2G supply power to Bus B7 d) V2G supply power to Bus B8 e) V2G supply power to Bus B10 f) V2G supply power to Bus B17 g) V2G supply power to Bus B19 h) V2G supply power to Bus B20 i) V2G supply power to Bus B21.

1) LOAD SHEDDING ALGORITHM

In case of load shedding algorithm as suggested in [25], $r_1(t)$, $r_2(t)$, $r_3(t)$, $r_4(t)$, $r_5(t)$, $r_6(t)$ and $r_7(t)$ represents the reserve required to avoid overloading conditions in IEEE-30 bus network as shown in part-A of Table 1. This reserve requirements can be fulfilled by providing an optimum value of nominal reserve r_o as mentioned in Eq. 7. Instead of providing r_o, the suggested algorithm in [25] used the concept of load shedding, i.e., $r_o = 0$. Therefore, the probabilistic randomness $R_G(t)$ in this case are, $R_{G_1}(t) = r_{o_1} - r_1(t) = 0 - 9.365 = -9.365$, $R_{G_2}(t) = r_{o_2} - r_2(t) = 0 - 29.513 = -29.513$ for $(N-1)$ contingency, $R_{G_2}(t) = r_{o_2} - r_2(t) = 0 - 29.713 = -29.713$ for $(N-1-1)$ contingency, $R_{G_3}(t) = r_{o_3} - r_3(t) = 0 - 2.991 = -2.991$, $R_{G_4}(t) = r_{o_4} - r_4(t) = 0 - 4.157 = -4.157$, $R_{G_5}(t) = r_{o_5} - r_5(t) = 0 - 2.126 = -2.126$, $R_{G_6}(t) = r_{0_6} - r_6(t) = 0 - 1.794 = -1.794$ and $R_{G_7}(t) = r_{o_7} - r_7(t) = 0 - 22.295 = -22.295$ as shown in part-A of Table 1. The negative sign represents the shedding of loads, i.e., shortage of active power on critical buses in IEEE-30 bus network.

2) V2G FUZZY COOPERATIVE CONTROL BASED ALGORITHM CONSIDERING N-1 CONTINGENCY IN IEEE-30 BUS NETWORK

To outperform the proposed algorithm in [25], we provide an optimum value of r_0 using V2G fuzzy cooperative control technology to compensate $r(t)$ in case of an arising of $(N-1)$ contingency in IEEE-30 bus network. Therefore, the probabilistic randomness $R_G(t)$ in our case are, $R_{G_1}(t) = r_{o_1} - r_1(t) = 9.437 - 9.365 = 0.072$, $R_{G_2}(t) = r_{o_2} - r_2(t) = 29.530 - 29.513 = 0.017$, $R_{G_3}(t) = r_{o_3} - r_3(t) = 3.052 - 2.991 = 0.061$, $R_{G_4}(t) = r_{o_4} - r_4(t) = 4.266 - 4.157 = 0.109$, $R_{G_5}(t) = r_{o_5} - r_5(t) = 2.197 - 2.126 = 0.071$, $R_{G_6}(t) = r_{o_6} - r_6(t) = 1.836 - 1.794 = 0.042$ and $R_{G_7}(t) = r_{o_7} - r_7(t) = 22.340 - 22.295 = 0.045$ as shown in part-B of Table 1. The positive sign represents the excess of supply on critical buses in IEEE-30 bus network. This will make an r_0 approaches to $r(t)$ as close as possible, i.e., minimizing $R_G(t)$ and therefore provide a synchronous stability between $G^f(t)$ and $D^f(t)$, as modelled in part D of Sec. III, i.e., Eq. 31 and 32. Fig. 7b shows the total active power supplied from V2G. This total active power from V2G is split between these critical buses (B7, B8, B10, B17, B19, B20 and B21) of IEEE-30 bus network according to their required demands detect by fuzzy controller as shown in Figs. 7c, 7d, 7e, 7f, 7g, 7h and 7i. In part-B of Table 1, we provide an optimum solution without shedding of loads using V2G fuzzy cooperative control based algorithm, considering $(N-1)$ contingency in IEEE-30 bus network, i.e., tripping of only Bus B7 due to occurrence of TPF as shown in Fig. 7a. Moreover, V2G only kicked in the power system at fault arising time, i.e., at t = 1s to compensate the deficit power on critical buses as shown in Fig. 4 due to tripping of Bus B7. This will enable the power system

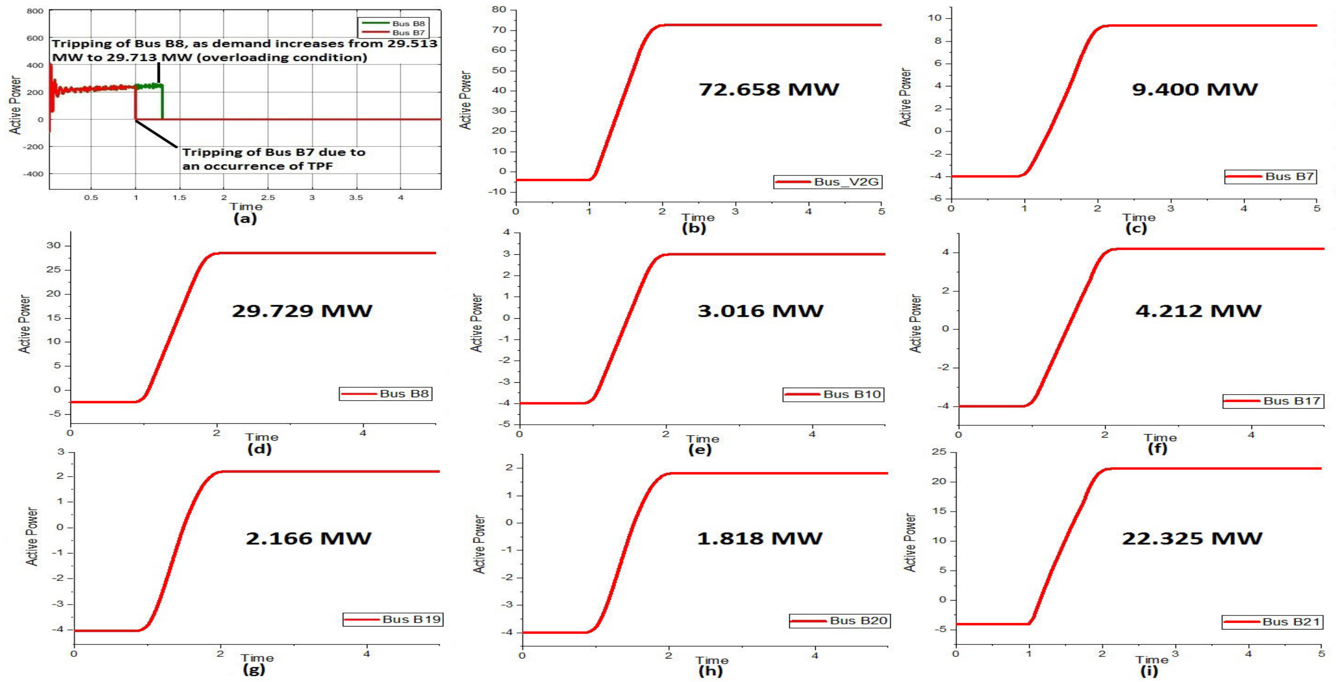

FIGURE 8. a) Tripping of Bus B7 and B8 at t = 1s and t = 1.3s (N-1-1 Contingency) b) total active power supply from V2G c) V2G supply power to Bus B7 d) V2G supply power to Bus B8 e) V2G supply power to Bus B10 f) V2G supply power to Bus B17 g) V2G supply power to Bus B19 h) V2G supply power to Bus B20 i) V2G supply power to Bus B21.

to return back to its normal demand conditions and avoid the collapsing of whole power system network in order to mitigate CFEs in IEEE-30 bus network.

3) V2G FUZZY COOPERATIVE CONTROL BASED ALGORITHM CONSIDERING N-1-1 CONTINGENCY IN IEEE-30 BUS NETWORK

Now, to verify the effectiveness of our proposed methodology, we considered a worst case scenario in the form of an occurrence of $(N-1-1)$ contingency in IEEE-30 bus network. In this case, we considered a scenario, in which the fluctuation of load is larger than the flexibility of the grid-side supply sources (V2G and wind power). That is, the maximum demand on Bus B8 as shown in Fig. 5 membership function increases from 29.513 MW to 29.713 MW, as shown in Fig. 6, as compared to collective supply from (V2G and wind power) on Bus B8, which is only 29.530 MW (r_{o_2}) as shown in part-B of Table 1. This is also verified from part-A of Table 1, where the required reserve $(r_2(t))$ on Bus B8 increases from 29.513 MW to 29.713 MW in case of an occurrence of $(N-1-1)$ contingency. This enhancement in demand level on Bus B8 will cause an overloading condition in IEEE-30 bus network, which leads to an occurrence of CFEs, i.e., tripping of Bus B8 along with Bus B7 as shown in Fig. 8a. At this stage, CFEs is inevitable and the only solution for network operators is to reduce its spreading towards other critical buses, i.e., Buses B10, B17, B19, B20 and B21 in IEEE-30 bus network as shown in Fig. 4. For this purpose, we upgraded our V2G cooperative control base algorithm as shown in part-C of Table 1. Now, to adjust the required demand of 29.713 MW on critical Bus B8, we upgrade the membership function of fuzzy controller, as shown in Fig. 5, especially for overloading mode, which increases from 29.513 MW to 29.713 MW. The upgraded membership function is shown in Fig. 6. Through this new membership function, we can easily adjust the required increased demand level on critical Bus B8. This can be done by shifting the surplus active power from critical Buses B7 $(R_{G_1}(t) = 0.072\ MW)$, B10 $(R_{G_3}(t) = 0.061\ MW)$, B17 $(R_{G_4}(t) = 0.109\ MW)$, B19 $(R_{G_5}(t) = 0.071\ MW)$, B20 $(R_{G_6}(t) = 0.042\ MW)$ and B21 $(R_{G_7}(t) = 0.045\ MW)$, as available in case of arising of $(N-1)$ contingency in IEEE-30 bus network towards the overloading Bus B8. This adjustment between collective supply of V2G and wind power and required demand levels on critical buses thorough fuzzy cooperative control mechanism is shown in Figs. 8b to 8i. The probabilistic randomness $R_G(t)$ in this case are, $R_{G_1}(t) = r_{o_1} - r_1(t) = 9.400 - 9.365 = 0.035$, $R_{G_2}(t) = r_{o_2} - r_2(t) = 29.729 - 29.713 = 0.016$, $R_{G_3}(t) = r_{o_3} - r_3(t) = 3.016 - 2.991 = 0.025$, $R_{G_4}(t) = r_{o_4} - r_4(t) = 4.212 - 4.157 = 0.055$, $R_{G_5}(t) = r_{o_5} - r_5(t) = 2.166 - 2.126 = 0.04$, $R_{G_6}(t) = r_{o_6} - r_6(t) = 1.818 - 1.794 = 0.024$ and $R_{G_7}(t) = r_{o_7} - r_7(t) = 22.325 - 22.295 = 0.03$ as shown in part-C of Table 1. In fact, we discovered from our simulation results that in worst case scenario of $(N-1-1)$ contingency issue in IEEE-30 bus network helps our algorithm to converge faster by reducing more the random deviation $R_G(t)$ between demand $(r(t))$ and supply (r_0) than it does for $(N-1)$ contingency issue. This is also verified by comparing the randomness $R_{G_1}(t)$, $R_{G_2}(t)$, $R_{G_3}(t)$, $R_{G_4}(t)$, $R_{G_5}(t)$, $R_{G_6}(t)$ and $R_{G_7}(t)$ as shown part- C $(N-1-1$ contingency) of Table 1, which is much lower as compared to randomnesses in in part-B $(N-1$ contingency) of Table 1. This will make an r_0 approaches to $r(t)$ as close as possible, i.e., minimizing $R_G(t)$ and therefore provide a synchronous stability between $G^f(t)$ and $D^f(t)$. Through this, we can easily mitigate the spreading of CFEs in IEEE-30 bus network in case of an occurrence of $(N-1-1)$ contingency issues. The complete flow chart of how our proposed algorithm works is shown in Fig. 13.

4) SUPERIORITY OF FUZZY CONTROL OVER TRADITIONAL CONTROL MECHANISMS

In CFEs, infrastructure interdependency and the uncertainties arises due to it is an important terms, which refers to cooperative relationship between different entities, i.e., nodes in a network [59]. This cooperative relationship between different nodes is totally dependent on the performance of each node. If any node breakdown occurred in network due to TPF and overloading conditions, i.e., failure of infrastructure interdependencies, then it will leads an uncertainties in a form of CFEs in a network. These uncertainties will have a different range of values. Due to this reason, they cannot be handled through traditional controller technique, which are based on deterministic values [33]–[36]. Therefore, to mitigate these CFEs, a fuzzy cooperative control system is proposed in this paper, which is based on fuzzy logic, a control protocol. These control protocols are defined by if-then rules in a form of membership functions, such as, if network operating in an overloading mode as shown in Figs. 5 and 6, then take decision by operating V2G along with wind turbines to mitigate the effect of these CFEs.

The sensitivity analysis of these infrastructure interdependencies due to TPF and overloading conditions is calculated using the fuzzy logic approach, as shown in the self-propagation graph in Fig. 3. Moreover, an uncertainty arises due to it in the form of CFEs is mitigated by operating V2G in the IEEE-30 bus network through generating a feedback signal from the fuzzy controller towards V2G as evident from the self-propagation graph in Fig. 3.

B. COMPENSATION OF TRANSIENTS RESPONSES USING V2G

Due to an occurrence of a post contingency issue in the form of $(N-1)$ and $(N-1-1)$ contingencies, transients occurred in power system network, which needs to be compensated within a short span of time. Same steps as discussed in part A of section IV are followed to determine the transients delays and provides its compensation using V2G. For this purpose, we first identified the critical buses using the self-propagation graph. Then the transients delay model, as expressed in (3), is then utilized to determine the transients delays in the IEEE-30 bus network. The accurate range of these transients delays is determined through a fuzzy controller. For this purpose, certain inputs related to transients delays are given to a fuzzy controller. The first input to the fuzzy controller is the transients delay factor, which is the ratio of A_{t_d} to A_d, as expressed in (3) and (9), i.e.,

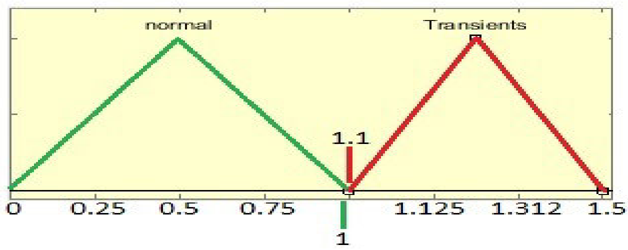

FIGURE 9. Membership function for normal and transients delay mode.

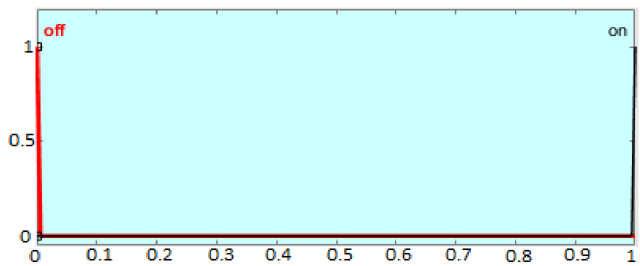

FIGURE 10. Output membership function of fuzzy controller.

$$T_{d_f} = \frac{A_{t_d}}{A_d} \quad (37)$$

T_{d_f} is only considered in IEEE-30 bus network, when $A_d > 0$, i.e., fault arises in power system network, in our case TPF occurred at Bus B7 from $t = 1s - 1.5s$, so $A_d = 0.5s$. The second input to fuzzy controller is the generator sensitivity factor (GSF), which is again computed in this case, i.e.,

$$GSF = \left(\frac{A_{t_d}^{new} - A_{t_d}^{0}}{\Delta P_{G_i}}\right) \quad (38)$$

This process is repeated for all generators connected in an IEEE-30 bus network. This will give us again a GSF matrix $(t_l \times g)$ for transients delays occurred in IEEE-30 bus network. The fuzzy controller is only operated, as fault arises at Bus B7 from $t = 1s - 1.5s$, as shown with transients delay membership function in Fig. 9. The generators connected in IEEE-30 bus network are disturbed only, when $GSF > 1$, i.e., after fault is occurred in power system network,

$$GSF = \left(\frac{A_{t_d}^{new} - A_{t_d}^{0}}{\Delta P_{G_i}}\right) > 1 \quad (39)$$

The input transients delay membership functions of fuzzy controller is shown in Fig. 9, which is in normal mode, when $T_{d_f} \leq 1$ and in transients delay mode, when $T_{d_f} \geq 1.1$. Whereas, the output function of fuzzy controller is shown in Fig. 10, which has two membership functions with on and off states for disturbance and normal condition.

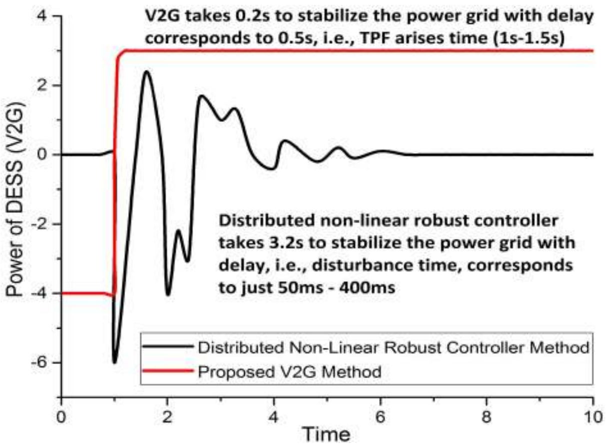

FIGURE 11. Transients compensation using V2G or distributed controller approach.

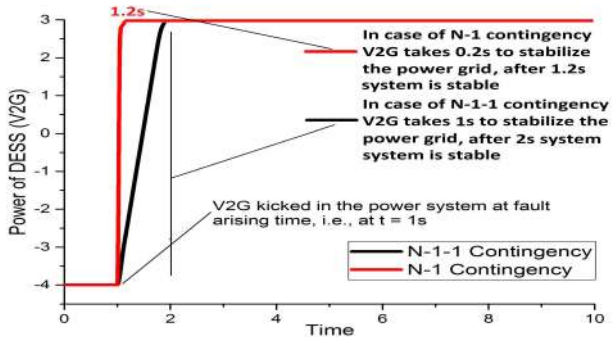

FIGURE 12. Effect on the stability of V2G in case of N-1 and N-1-1 contingencies.

After this, a signal is generated from a fuzzy controller towards V2G to mitigate these transients delay issues. V2G has a strong capability to mitigate these transients delays within a short period. To verify this, we compared our advanced technique with the one proposed in [58]. Reference [58] proposed an algorithm based on a distributed non-linear robust controller, which provides stabilization to the power grid in 3.2s considering the fault latency rate in between 50ms-400ms. This prolonged stabilization delay of 3.2s will make the network vulnerable to CFEs [31], [32], especially after an occurrence of post contingency issues. Therefore, there is a need to stabilize the power grid in a short period, even if the fault latency rate is high, as in our case (a TPF arising time is 0.5s). This phenomenon is verified through Fig. 11, in which V2G technology takes 0.2s to stabilized the power grid with the TPF latency rate of 0.5s. Whereas, distributed robust non-linear controller takes 3.2s for stabilizing the power grid, considering a fault latency rate in between 50ms-400ms after an occurrence of CFEs in a power system network.

1) EFFECT OF CFEs ON THE STABILITY OF WIND AND V2G POWER

As wind power is an unreliable resource of energy, therefore when the system is faced with CFEs, the stability of wind power may also be endangered [60]–[62]. This phenomena is verified in Fig. 7a ($N - 1$ contingency), i.e., tripping of Bus B7, and Fig. 8a ($N - 1 - 1$ contingency), i.e., tripping of Buses B7 and B8. In this case, an energy storage system (ESS) in the form of V2G, which provides a constant and stable power is considered to be an effective tool for enhancing the controllability and flexibility, not only for wind farms but also for the entire power grid [63], [64].

As far as concern the stability of V2G, when the system is faced with CFEs, it is totally dependent on two factors:

1) Deployment location of V2G operation [65], [66],
2) Severity of CFEs (worst-case scenario, ($N - 1 - 1$) contingency) [67]

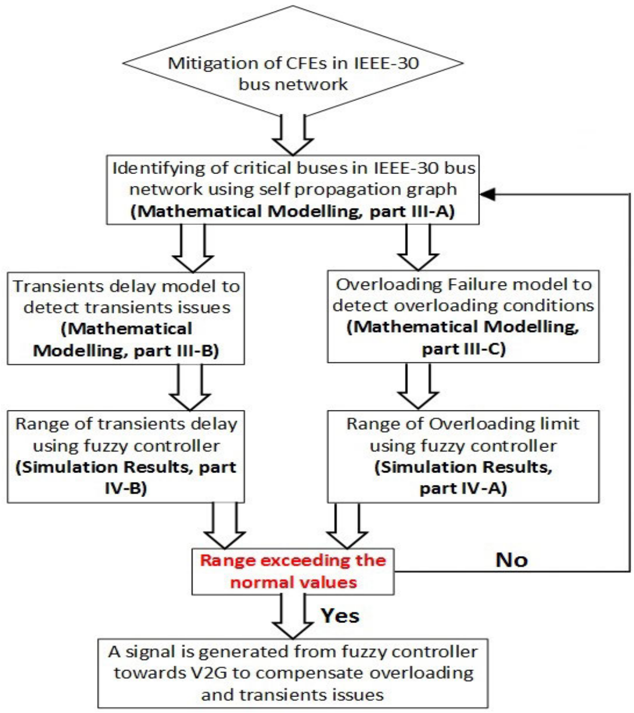

FIGURE 13. Working of the proposed methodology to mitigate CFEs in IEEE-30 bus network using V2G cooperative control technology based on a fuzzy logic approach.

Considering (1), the relationship of power system survivability against CFEs, when ESS in the form of V2G is deployed totally depends on its deployment location [65], [66]. The complete simulation study of how accurate ESS deployment in power grid will reduce the endangered, i.e., instability of ESS, when the system is faced with CFEs is performed in [65]. This means that V2G needs to be deployed at the most critical location in the power system in order to achieve the best defensive mechanism. For this purpose, we used the concept of self-propagation graph, as shown in Fig. 3. Through this, we can easily find out the critical locations, i.e., Buses B7, B8, B10, B17, B19, B20, and B21 in the IEEE-30 bus network, as highlighted in Fig. 4 and therefore deployed V2G in the most optimum location. Through this technique of finding out the optimum spot location for V2G operation in a power grid, we can easily mitigate the endangered caused by CFEs to the stability of V2G operation. Rather, in this case, V2G operation in power grid acts as the best prevention mechanism against CFEs.

Secondly, considering (2), i.e., worst-case scenario, in which $(N-1-1)$ contingency occurred in the IEEE-30 bus network, there is a delay occurred in the stability response behavior of V2G. This phenomenon is verified through Fig. 12, in which V2G technology takes 0.2s to stabilize the power grid in case of an occurrence of $(N-1)$ contingency. Whereas, in the case of $(N-1-1)$ contingency, V2G takes a delay of 1s to stabilize the power grid completely.

V. CONCLUSION

In this paper, a detailed simulation analysis of CFEs in the power system is discussed. The CFEs was simulated on critical transmission lines in the IEEE-30 bus network. It was concluded from simulation results that after occurrence of $(N-1)$ and $(N-1-1)$ contingencies, CFEs are then inevitable. At this stage, the power network operators can only reduce the spreading of CFEs. The previously proposed algorithms suggesting different load shedding schemes to compensate these CFEs, which incur losses into the power system network. To tackle this problem, a cooperative control strategy based on V2G technology using a fuzzy controller is proposed in this paper. This approach provides optimal solution by mitigating the spreading of CFEs in the IEEE-30 bus network without performing load shedding or taking preventive measures. This mechanism improves the security and safety of the power system network by considering all critical power constraints while preventing CFEs in post contingency events.

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